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A review of thermodynamics and heat transfer in solar refrigeration system

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A B S T R A C T

Solar energy is one of the most efficient, clean and affordable energy alternatives available today. With the current concerns about global warming and ever increasing energy rates, countries are seriously looking for domestic and industrial usage of solar energy. In the present study, a detail review of the application of solar energy for refrigeration systems has been carried out. The utilization of solar energy for refrigeration systems would help in improvement of energy economics, energy consumption and energy efficiency. The review focuses especially on solar panel, desiccant fluid for icemaker and its components. The study also includes thermodynamic equation and material for making component of refrigeration to improve the coefficient of performance. Study around the economic evaluation and solar performance coefficient in the type of refrigerator, modeling and simulation, mathematical equation of heat transfer and type of absorption used are other topics that could be considered.

Contents

1. Introduction

Most countries are using fossil fuels in various sectors such as transportation, commercial, institutional, domestic, etc. The usage of this fuel is creating serious problems for the modern society. Fossil fuel is a limited source of energy. It is important to find an alternative to fossil fuel before this resource comes to an end. The

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Nomenclature

A_c	aperture area
COP	coefficient of performance
C	concentration of solute
M	mass
a	thermal diffusivity
B	volumetric thermal expansion coefficient
ψ_r	reversible absorption refrigerator
η_s	efficiency
C_p	specific heat capacity
ρ	density
V	velocity
K	conductive heat transfer coefficient
K_T	monthly average cleanness index
T_g	temperature of generator
T_c	temperature of condenser
T_{eva}	temperature of evaporator
T_a	temperature of adsorbed
P_{cn}	saturation pressure
$\dot{Q}_g$	heat of generator
Q_{eva}	heat of evaporator
Q_c	heat of condense
U_L	overall heat transfer loss coefficient
W_p	input power of pump
W	width of aperture for parabolic solar collector
h	enthalpy
H	monthly average daily radiation on a horizontal surface
H_0	monthly average daily extra-terrestrial radiation

burning of fossil fuel is also causing global warming (i.e. greenhouse gas effect) [1–3], which is a major concern of present times. The import of fossil fuel has a substantial effect on the economy of a country. The most convenient option to handle this issue is renewable energy.

1.1. Renewable energy

The developed countries of the world are spending enormously to achieve renewable-energy technology. Using the wind energy is increasing dramatically. It can be studied that in most European countries like Germany and Netherland wind turbines are used in the west and north for generating electricity [4]. Also some Asian countries use the wind energy. In the north of Iran (Mangil city) there are a lot of wind turbines for generating electricity and also in the north-west of Iran, there is mineral material which is used for geothermal energy [5]. More than seventy percent (70%) of the factories in Iceland use geothermal energy for the industrial purpose [6]. This type of energy is cheaper than fossil fuel, and it can also reduce pollution.

1.2. Solar energy

Solar energy is the most common type of renewable energy presently being used by most of the countries. Low price and cleanliness are some of the advantages of this type of energy. For example, central and south-east of rural areas in Iran use solar heated water [7]. It can be used in the industrial field like a power plant. From year 2001 Sweden has been exploiting a power plant working with solar-energy [8]. Fig. 1 presents a sample of a solar power plant. Its components include the solar collector's array (No. 1), which has approximately 10,000 m^2 collectors. And heat exchanger (No.2) which works with solar energy, the component number (4) is a boiler and increases the temperature. Normally, in solar power plants two types of heat exchanger are used. After exiting from boiler, hot water must enter the heat exchanger (No. 5). It can be seen that the efficiency in this type of systems is higher than the systems working on only one heat exchanger.

On the other hand, using the solar energy for cooling systems is also considerable (Fig. 2). It can be said that in cooling systems operating with two cycles, low temperature cycle works at the maximum temperature of about 100 °C [9].

Solar energy can be used for water heating, ovens, refrigerators and ice makers [10]. There is a huge potential for using solar energy in the private sector. Several innovated concepts of solar panels and collectors with more efficiency than the previous ones are being developed [11]. Most of the designs come from the tests performed on electric instrument. In Madrid, for instance, during the summer of 2003, some experimental tests were done on hot water to calculate the properties of solar panel for the water heater. Another test was also done on ($LiBr/H_2O$) for calculating COP of a cooling system [12,13]. In the middle of 1990s at the University of Queensland in Australia, application of desiccant absorber in the air-condition systems was tested, and it was seen that it can be used in a dry and low-humidity environment. Function of solar refrigerant systems working with Zeolite was tested in the South of Europe and in some African countries afterwards, their government used solar technology for rural areas [14]. But in some places, there was no historical data available for analysis as in South Africa in SANAE IV [15]. By knowing the latitude and longitude and also calculating the number of days the value of solar radiation in a specific place can be estimated. Flat plate solar collectors play an important role in solar technology. To improve the efficiency both sides of collectors are insulated [16]. It is located along the south–north at a tilt angle of latitude plus 15 [17]. Monthly average cleanness index (k_T) is the ratio of average daily radiation for a month on a horizontal surface (H) to the average daily extraterrestrial

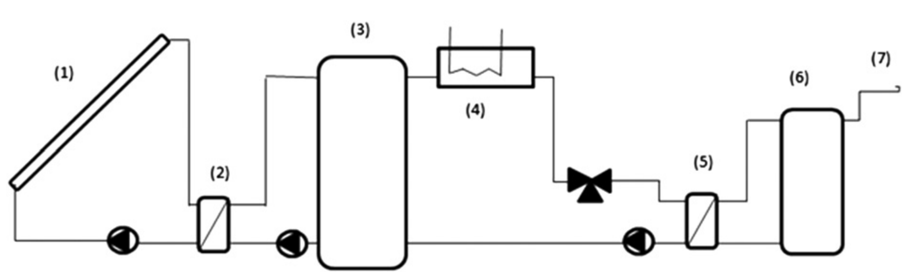

Fig. 1. Scheme of solar energy system [8].

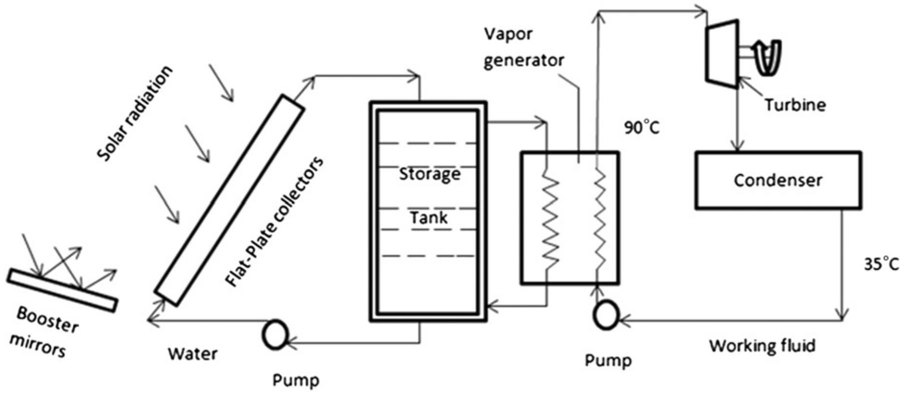

Fig. 2. Low-temperature power generation [9].

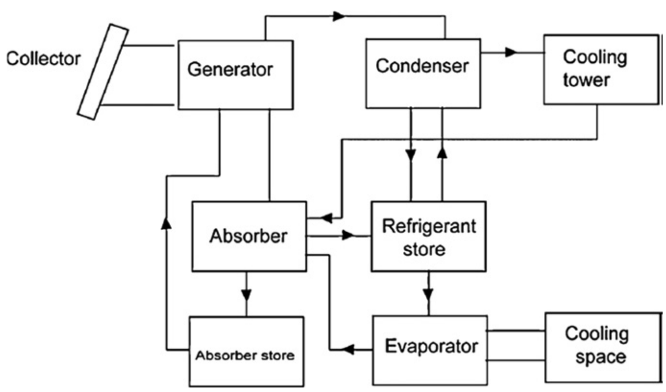

Fig. 3. Block diagram of a typical solar cooling system with refrigerant storage [21].

radiation (H_0) [18]

$$k_T = \frac{H}{H_0} \quad (1)$$

1.3. Solar refrigerators

Solar refrigeration system is used in agricultural sector where storing and maintenance of crops is very important and having the access to electricity is so difficult. Therefore solar refrigerator can be called as the agricultural products storage [19]. Besides this, some of the areas which have a good solar potential like the sub-Sahara countries, using the solar refrigerator is necessary for keeping some of the medicine. This type of refrigerator should be used to store medication tools like vaccination which needs to be stored at low temperature. Without doubt, this type of refrigerator can be moved from one place to another [20]. Solar energy is widely used for air conditioning and refrigeration. It reduces the consumption of electricity per unit residential area. It also helps to avoid the use of Freon refrigerant or other harmful gases that damage ozone layers [21–24]. Instead of Freon gas, solar refrigerators use desiccant gas, LiCl, LiBr or water. None of these gases are harmful to the environment and refrigeration system can work with a high coefficient of performance (COP) [25]. The voltage of a unit is improved by using a solar panel in the refrigeration system [26]. Using Zeolite or water improves COP of the ice maker [25]. The block diagram of the typical solar cooling system with refrigerant storage is shown in Fig. 3.

Countries are looking forward to using solar energy for a cooling system. Majority of these countries try to make refrigerant systems, which can be both more efficient and have good benefit in terms of economical point of view. For instance, in the middle of 1980s, China achieved an improvement in the making of solar refrigerators which worked with LiBr [27]. The mechanisms for these systems were simple; first of all, energy was generated in the flat solar collector, and then it operated just like every other refrigeration system. A schematic diagram of the primary design for a solar refrigerator is shown in Figs. 4 and 5 [28,29].

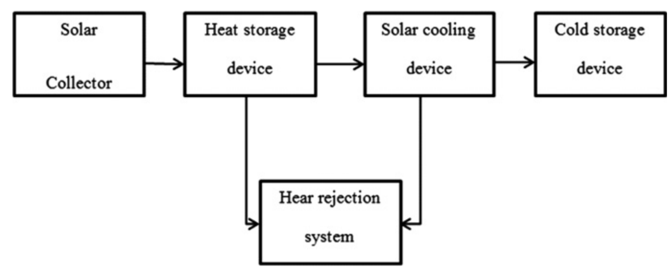

Fig. 4. Schematic diagram of refrigerator system [29].

2. Adsorption system

2.1. Adsorption

Adsorption is a process where binding forces between fluid molecules and the solid medium have an electrostatic origin [30]. Solar adsorption cooling systems are of two types, low pressure and high pressure. For the instruments working at low pressure, it is not necessary that a gap test be done because in the first process of manufacturing material and welding type are selected carefully. On the other hand, for the instruments designed to operate at high pressure, it is necessary to perform a gap test and temperature test several times [31]. Adsorption refrigeration cycle relies on the adsorption of a refrigerant gas on an adsorbent at low pressure and subsequent desorption by heating the adsorbent. It acts as a chemical compressor driven by heat [32]. Carbon methanol is commonly used as the single-purpose solar adsorption refrigerant [31]. Methanol is a good adsorbent, because of its ability to evaporate at a temperature below 0 °C. Its enthalpy of vaporization is high, and it can be vapored in a wide range of temperatures. Methanol is able to work at low pressures. Since the coefficient performance of activated Carbone is not high, the new Carbone adsorption material is being used in the some of the refrigerant system like activated Carbone and hydrogen and activated Carbone and nitrogen [33].The melting point of methanol is −93 °C [34]. Among different types of activated Carbone adsorbent, activated Carbone with ethanol

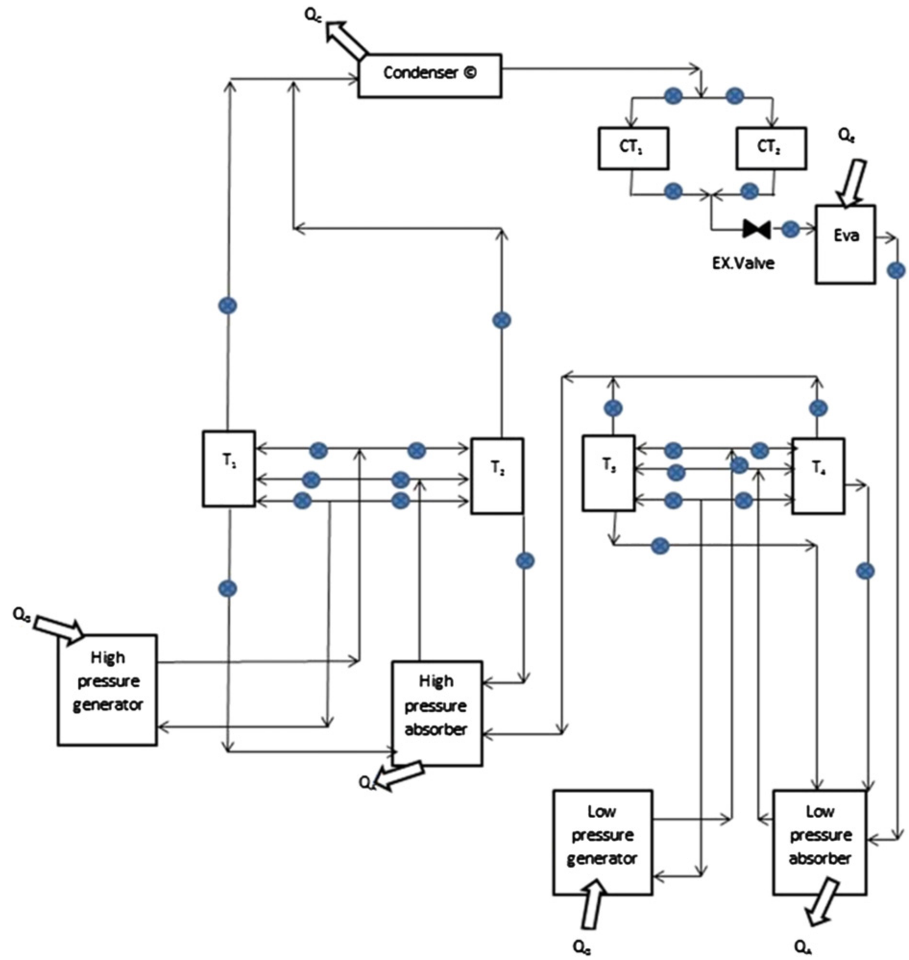

Fig. 5. Schematic diagram of refrigerator system (two stages) [28].

has the better performance. Generally speaking, different types of the adsorbent can help to achieve coefficient of performance of solar refrigerator system and specific cooling effect [35].

2.2. Desiccant cooling

Desiccant cooling is used in the open cycles. In open cycles water from air is released into the atmosphere after the desorption process [36]. Desiccant technology is used in various types of industries. The use of air conditioning and refrigerator technology is increasing dramatically. It leads to problems such as high energy consumption, emission of CO_2 and other GHGs. Desiccant technology does not need ozone depleting refrigerant, and it can work using natural gas and solar thermal energy [37]. Desiccant systems can be used to improve the performance of evaporating cooling system. The combination of the desiccant wheel with the conventional vapor compression chiller can also increase the efficiency of the later [36]. Apart from the refrigeration system desiccant, technology can also be used for thermal system and storing solar energy. For example, when the solar thermal energy is not needed for the operation of the desiccant cooling system or for other utilizations, the collected solar energy can be stored in the thermal storage tank [38].

2.3. Solar absorption refrigeration

Solar absorption refrigeration is based on the coefficient of performance of the refrigerator. From thermodynamics, the COP of the reversible absorption refrigerator can be calculated by following equation [39] :

$$\psi_r = \frac{\left[\left(\frac{1}{T_a}\right)-\left(\frac{1}{T_g}\right)\right]+n\left[\left(\frac{1}{T_c}\right)-\left(\frac{1}{T_g}\right)\right]}{\left[\left(\frac{1}{T_e}\right)-\left(\frac{1}{T_a}\right)\right]+n\left[\left(\frac{1}{T_e}\right)-\left(\frac{1}{T_c}\right)\right]} \tag{2}$$

Heat exchange diagram has been shown in Fig. 6.

A solar operated absorption refrigeration system is made of solar collector and refrigeration cycle. Generally, a reversible absorption refrigerator has four main components and each of them can generate heat in the cycle. Fig. 7 shows this diagram.

Zeolite-13X is commonly used as an adsorbent material in the adsorption cycle. Most of adsorbents, when applied in the reversible absorption refrigeration, must pass through all parts of the refrigeration systems but Zeolite-13X can be converted without moving from one part to another. It is being applied in the adsorption cycle with water [40]. The adsorption and desorption heat is less than others. It is between 3300 and 4000 kJ/kg and its temperature is high, which is around 70 and 200 °C [41]. Therefore, the performance of Zeolite-water is lower than activated Carbone–methanol system. There is a relationship between water vapor pressure and water content. Fig. 8 shows the relationship between p-dry bases. There is also an inverse relationship between temperature of liquid and percentage of water content. When the temperature is high, the percentage will be low. It can be seen that at temperature of 25 °C, the percentage of water content is over 0.2.

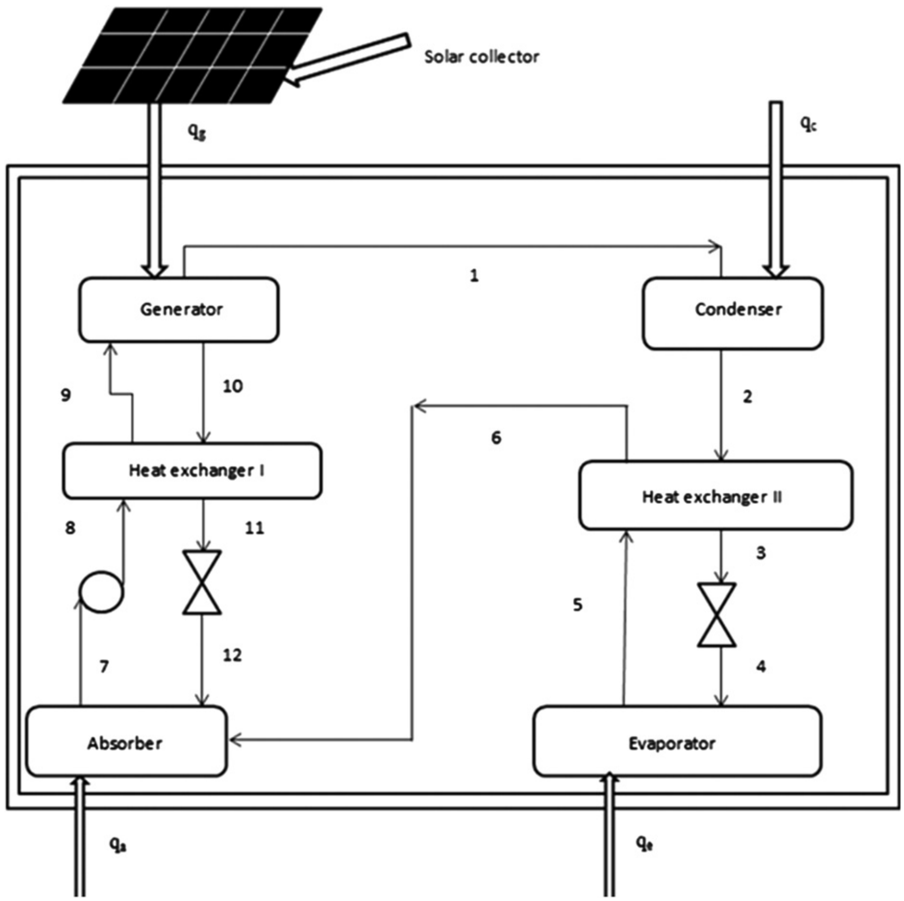

Fig. 6. Solar absorption refrigerator [39].

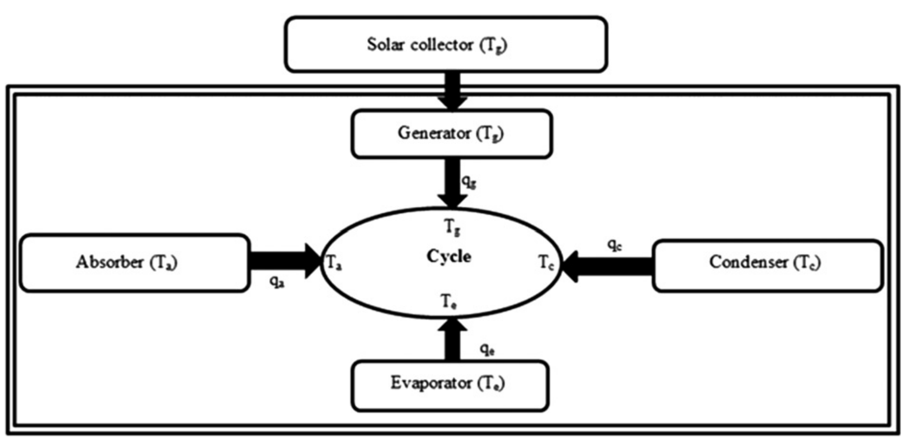

Fig. 7. Completely reversible absorption refrigerator [39].

Calcium chloride can be absorbed in solar refrigeration cycle. The resulting compound can be represented by the following chemical equations [42]:

$$CaCl_2 \cdot 8NH_3 + \Delta H_1 \leftrightarrow CaCl_2 \cdot 4NH_3 + 4NH_3$$

$$CaCl_2 \cdot 4NH_3 + \Delta H_2 \leftrightarrow CaCl_2 \cdot 2NH_3 + 2NH_3$$

$$CaCl_2 \cdot 2NH_3 + \Delta H_3 \leftrightarrow CaCl_2 + 2NH_3$$

The equilibrium temperature for this type of absorption is [43]

$$\left(\frac{-l}{T_{e1}}\right) = \left[2.06\ \log(P_{cn}) - 32.867\right] 10^{-4} \tag{3}$$

$$\left(\frac{-l}{T_{e2}}\right) = \left[2.06\ \log(P_{cn}) - 31.997\right] 10^{-4} \tag{4}$$

Another type of absorption is the one by LiBr/H_2O. It has high performance in the solar refrigeration system. This kind of refrigeration has low efficiency. To get a higher efficiency, it has

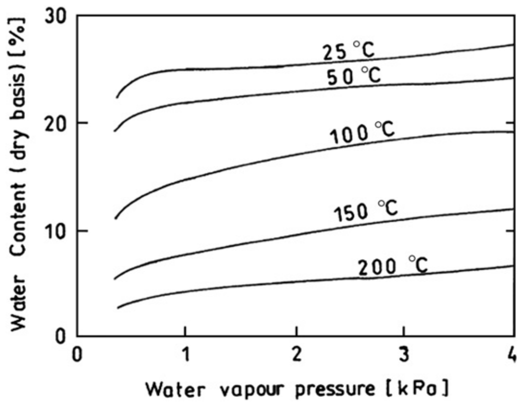

Fig. 8. Relationship between p-dry bases (%) [40].

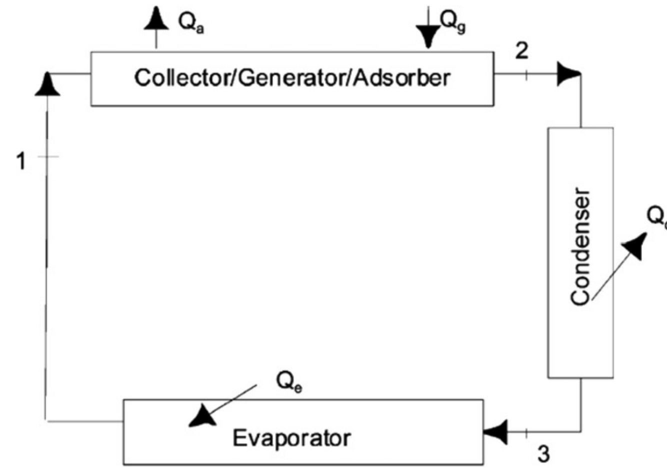

Fig. 9. Simple adsorption diagram [62].

been designed as the double effect [44,45]. Another case is water–ammonia where water is the absorbent and NH_3 is the refrigerant. In both cases the absorbent and generator work same as the compressor system [46].

There are three different approximation levels for these types of absorption. Firstly, producing high pressure, then energy generation for running the gas and vapor and last but not the least transferring the mixture of vapor and gas [47].

3. COP and thermodynamic analysis

3.1. COP

The coefficient of performance for solar refrigerator is not calculated only in one way. It depends on adsorbent, which is being used in the refrigeration. The solar refrigeration which works by $LiBr/H_2O$ coefficient of performance is the ratio of heat of evaporator to the sum of generated heat and input power to the pump [48,49].

$$COP = \frac{Q_{eva}}{IA_c + Q_y + W_p} \tag{5}$$

Coefficient of performance of the absorption cooling machine is calculated as a function of the process temperature of the frigorific machine, namely the condensation temperature (T_{con}) and the evaporation temperature (T_{eva}) [50]. When it comes to ice makers, COP is calculated in a different way. Aside from the temperature of condenser and evaporator, it would depend on the available solar-energy factors. It is defined as the ratio of total heat extracted by evaporation of the desorbed mass of methanol to the total incident global irradiance [51–53].

$$COP_s = \frac{useful\ effect}{Available\ solar\ energy} = \frac{m[L - c_{pl}(T_c - T_e)]}{S_0 \int_{sunset}^{sunrise} G(t)dt} \tag{6}$$

For each day, the calculated gross solar coefficient of performance is defined as the ratio of heat extracted by evaporation of water to the solar heat supply [54,55].

$$COP_{SR} = \frac{Q_e}{Q_h} \tag{7}$$

For refrigeration with combined hybrid system, the coefficient of performance is defined for day and night separately [56].

$$COP_{Day} = \int_{Cooling}^{Day} Qdt \tag{8}$$

$$COP_{Night} = \frac{\int_{Cooling}^{Night} Qdt}{\int I(t)A_c dt} \tag{9}$$

$$COP_{tot} = COP_{Day} + COP_{Night} \tag{10}$$

3.2. Thermodynamic analysis

Normally gases used in the refrigerator are R22 and R12. The choice of refrigerant as a working fluid in refrigerating machines and heat pump compression must depend on thermodynamic, technical, environmental and commercial constraints [57–60]. When a high pressure in the compressor unit is accomplished, vapor and adsorbent become separated [61]. The rate of heat absorbed at the junction between two dissimilar materials is given by

$$Q = \alpha ABIT \tag{11}$$

Fig. 9 shows simple diagram of adsorption cycle having the three main components of solar refrigerator. The values of internal and external heat have been illustrated [62].

The value of heat is calculated for the collector by the following equation:

$$Q_g = m_a c_{pa} \Delta T_a + (m_{r,i} - m_{r,g}) c_{pr} \Delta T_r + m_{r,g}(h_2 - h_1) + m_{r,g} h_{sg} \tag{12}$$

The amount of heat for evaporator and condenser is calculated by the following equations:

$$Q_e = m_{r,g}(h_1 - h_3) \tag{13}$$

$$Q_c = m_{r,g}(h_2 - h_3) \tag{14}$$

For the absorbent in the solar refrigerator working in two stages, that is shown in Fig. 10. First of all, there are t_c and t_o, and they are the same. In the isotropic process, the pressure is high and after processing at the same pressure the temperature reaches t_{gh}. In the second stage, it will be t_{gl} when the cycle is going through an isotropic process and finally it will reach t_c.

When it comes to thermodynamics, there exists a major problem for the solar refrigeration. Although several adsorbent for this mechanism is used, its COP does not increase considerably. Perhaps Zeolite-13X becomes the only adsorbent liquid and has high COP as well. It is based on minimum evaporating temperature, and can be compared with the traditional absorption [63].

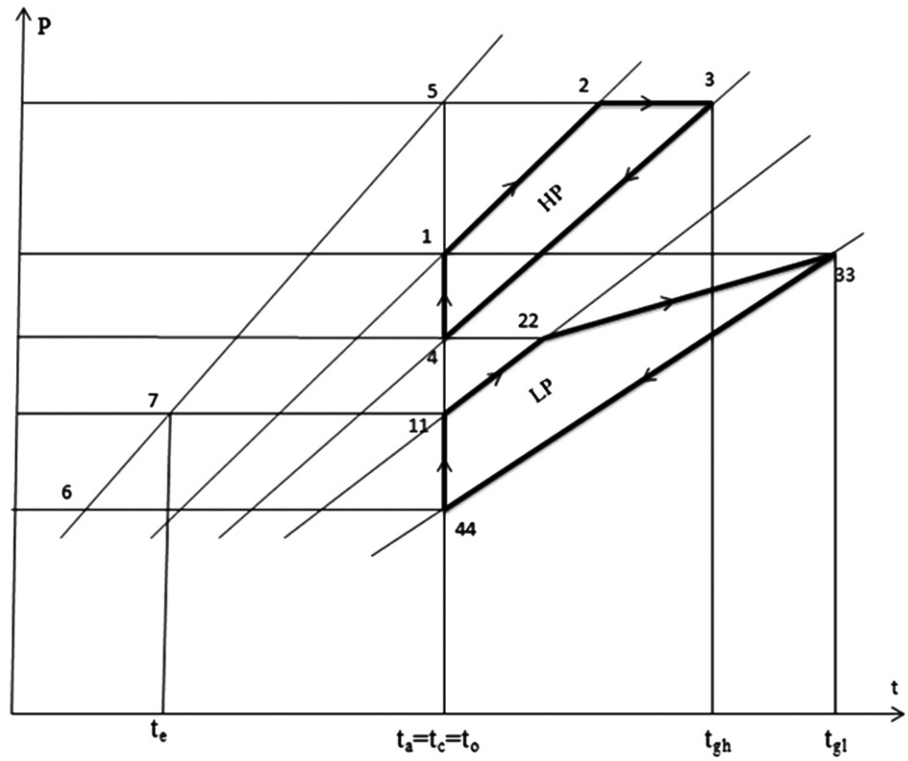

Fig. 10. Thermodynamic diagram of the modified two stages intermittent solar refrigerator [20].

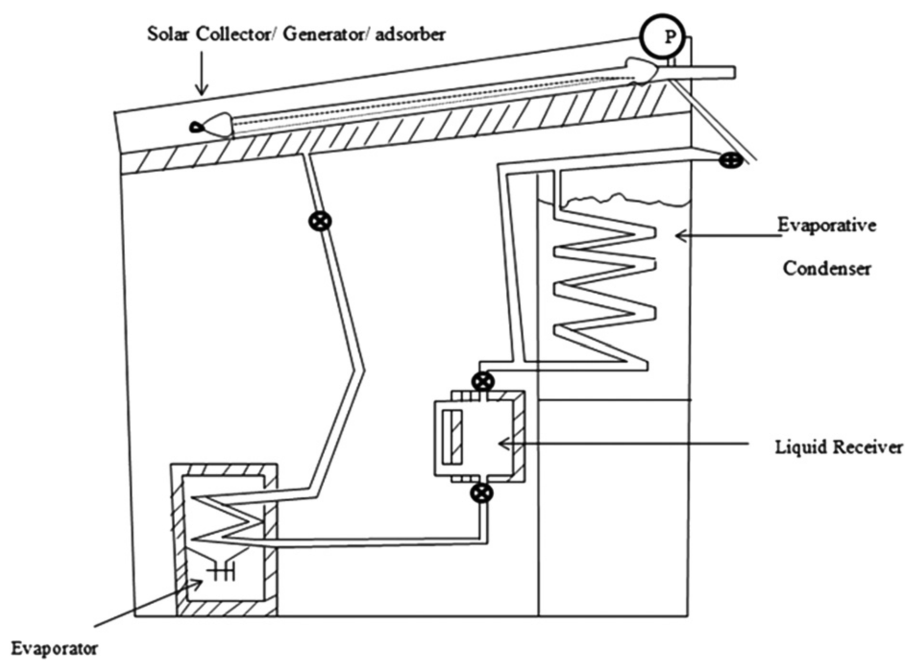

Fig. 11. Schematic of the activated carbon–methanol refrigerator [68].

3.2.1. Heat transfer

The most important factor in designing a solar refrigerator system is the collector plate, where heat transfer plays an important role. Using carbon–methanol material between two layers of solar collector can be advantageous that is shown in Fig. 11. Normally, it is made up of double layer of collectors, and it has a small space between the layers. It is covered by carbon methanol liquid. Carbon methanol liquid is used so that heat transfer does not occur between the collectors to outer space and as a result a higher efficiency is achieved. Also, heat is not dissipated into outer space at night meaning that in the night time, the energy could be consumed in systems, and heat will be trapped between the layers [64–66]. On the other hand, there are some parameters that can improve the coefficient of performance. Angle of flat collectors and their materials, weight of carbon methanol liquid and size of collectors are among the parameters

that affect the COP of refrigerator systems. For solar ice-maker and refrigeration systems, the parameters of adsorbent bed are the most important [67]. For these types of solid adsorptions, there is an energy balance equation for the collector and adsorbent plate [68].

$$\rho c_p \frac{\partial T}{\partial t} = Q_n - U_L(T - T_{am}) + \dot{Q}_g + K\frac{\partial^2 T}{\partial x^2} \tag{15}$$

$$\dot{Q}_g = h_{sg} m_{ad} \frac{dX}{dt} \tag{16}$$

Another way of improving the COP of the solar refrigerator is to change the structure of coal bed in concentric tube configuration. The coal in the tube can be exploited. It can be useful because there is a significant amount of heat trapped here compared to the previous situation. The activated coal is located between the distributor and external cylinder [69]. Mass and heat balance around the evaporation yields the following two coupled differential equations [70]:

$$\text{Mass balance}: \frac{d}{dt}(\rho VC)_{EC} = mC \tag{17}$$

$$\text{Heat balance}: \frac{d}{dt}(\rho V c_p T)_{EC} = Q_{in} + mc_p T - mh_T - Q_{out} \tag{18}$$

For the evaporator and condenser, we will be able to calculate the amount of energy and mass by using the thermodynamic equations. According to the first law of thermodynamics, it can be assumed that the steady-state flow in the systems and the amount of internal energy could be calculated. By using the mass and heat balance, we can calculate the value of liquid flowing into the evaporator and condenser [71].

$$\frac{dm}{dx} = m_a \frac{dT_a}{dx} \tag{19}$$

3.2.2. Evaporator

In the solar refrigerator, the main components are designed a bit differently from the normal refrigerator. For example, the refrigeration that works with absorbed Lithium Bromide contains two different vessels. The top glass vessel contains water in order to simulate the condition of the condenser in the absorption refrigerator. The bottom glass vessel contains a heat exchanger to act as the evaporator, the distributor heater to drop water droplets on the heat exchanger, and a stagnate pool of Lithium Bromide–water solution of strong concentration to act as the absorber [72,73]. Fig. 12 shows the evaporator for solar refrigerator system [74].

For the water in evaporator, it is assumed that the rate of absorption of absorbate equals that of evaporation. There is a layer above the evaporator in the ice maker, containing an amount of cold water and it prevents heat transfer with the outer layer, and it also leads to heat transfer between cold water and adsorbent at a stable temperature [75,76]. For condenser and heat exchanger the most important factor is to use the ambient air for natural convection cooling, because condenser and absorber are dependent on each other [77]. As far as material is considered, the selection is quite important for the refrigerator. When it comes to generator and heat exchanger, they must be fabricated from special material with easy transfer between two fluids, and the rest of the equipment is equipped with pipes having fins to enhance the heat exchange between the surrounding air [78]. Sometimes metals are chosen for the body of the main component because they have a very high conductivity according to the solution of Maxwell's equations and electromagnetic property models [79].

3.3. Collector

The most important part in the solar refrigeration system is the collector. Efficiency in thermal engines or coefficient of performance in cooling systems depends on temperature. The efficiency of collector can be calculated by the following equation [80]:

$$\eta_s = \frac{Q_H}{Q_i} \tag{20}$$

$$Q_H = I_c A_H - Q_R \tag{21}$$

The energy balance equation can be estimated by the following equation for the collector plate [81]:

$$\rho c_p A \frac{dT_{p1}}{dt} = I_n - U_L(T_{p1} - T_{am}) + KA\frac{d^2 T_{p1}}{dx^2} \tag{22}$$

Sometimes, parabolic solar collector is used instead of plate collector. Although designing trough collectors is difficult and requires high costs, it has comparatively high efficiency in cooling

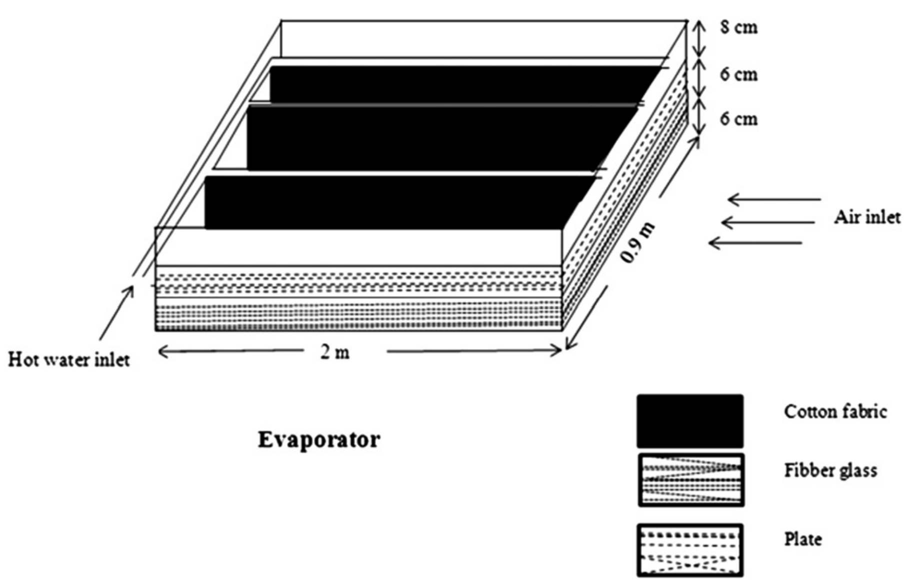

Fig. 12. Schematic of the evaporator [74].

and thermal system. They are used in power plants but with a specific design so that they could be used in the small system [82]. The efficiency of this type of collector in the cooling system is ratio of the useful energy produced to any time period to the beam radiation incident on the collector [83]. It is expressed by the following equation:

$$\eta = \frac{\dot{m} f c_{pf} (T_{out} - T_{in})}{IWL_c} \tag{23}$$

Solar photovoltaic can be defined as the conversion of the sun's radiation into electricity. Photovoltaic systems can be used in many ways. For example, rural electrification, water pumping, vaccine refrigeration, etc. [84]. Photovoltaic systems could also be used for domestic appliances such as lightning, radio and TV operation [85]. The reliability factor of the photovoltaic system can be estimated by probability of loss of the supply and availability factors [86]. Some of the solar refrigerators use the photovoltaic panel. It can be useful for the generator system. It can save and provide back-up electricity for solar refrigerator [87]. Sometimes, in the design of solar refrigerator systems along with photovoltaic system, a solar PV generator and a battery of accumulators is chosen [88]. To have a high coefficient of performance, two solar systems with PV cells, compression and thermal solar collector (30–50% efficiency of each collector) are used [89].

3.3.1. *Freezing system*

The theory of freezing solar cooling depends on temperature. The adsorbent used is carbon–methanol. Using active Carbone, the temperature varies between day time and night time. In the morning, the adsorbent can save the solar energy, and its temperature rises sharply. As far as the carbon methanol adsorption is considered, it is done by the thin layer. When the solar radiation is too weak the evaporator temperature will be low. As a result active carbon starts to adsorb methanol stream [90]. Finally, it will be used to transfer the heat into the outer space. However it cannot be useful for the system. The cooling system will permit the closing of the gate which is located between the flat collector and evaporator [91].

4. Conclusion

To sum up, a majority of countries have been trying to exploit renewable energy more than before which can bring a lot of benefits to their societies. Firstly, using fossil fuels can generate pollution and release greenhouse gases into the environment which are harmful to mankind and have adverse effect on environment. Secondly, unlike fossil fuel energy, renewable energy is unlimited and will never come to an end. And finally, the use of fossil fuels is expensive, and it could have unfavorable effects on the economic system of a country. It is mentionable that among renewable energies, solar energy is more accessible, and it has more applications in different countries. Solar collector can be useful either in the industrial or private sector. Most of the equipments used at home would be able to work with solar energy and would have good efficiency if designed perfectly. Nowadays, most of the European countries are designing solar refrigerator with high efficiency of performance and are also improving the adsorption system. The solar ice-makers are being used more than before. Using the benefits of warm sources for cooling systems is the most important point to be remembered when considering the use of solar energy.

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